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NORTHERN OIL AND GAS ACTION PROGRAM

PROJECT B-2: CRITICAL ESTUARINE AND MARINE HABITATS
OF THE CANADIAN ARCTIC COASTAL SHELF

SUBPROJECT B-2-1: BEAUFORT SHELF FISH HABITAT RESEARCH

ANALYSIS OF SATELLITE DIGITAL IMAGERY IN SUPPORT OF DFO OCEANOGRAPHIC OPERATIONS IN THE BEAUFORT SEA

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by

Dr. Gary A. Borstad

G.A. Borstad Ltd.
10474 Resthaven Drive
Sidney, British Columbia, Canada, V8L 3H7

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Prepared for

Department of Fisheries and Oceans
501 University Crescent
Winnipeg, Manitoba
R3T 2N6

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Introduction

This document describes work carried out under ther terms of NOGAP Project No. 2 of the Beaufort Shelf Fish Habitat Study. Thermal and broad-band visible imagery from the NOAA 7 satellite was obtained over the Southern Beaufort Sea during the months of July, August and September 1984. Digital data was then analyzed to produce maps of sea surface temperature and turbidity in support of DFO oceanographic operations in the area.

Data Aquisition

NOAA 7 satellite imagery of the Southern Beaufort Sea was obtained in digital form from two sources. Band 2, 3 and 4 imagery for July was obtained from the Atmospheric Environment Service Arctic Weather Central in Edmonton on arrangement by Dr. M. Lawrence. Bands 1 to 5 imagery for the months of August and September was acquired from the Department of Oceanography, University of British Columbia as part of the 1984 bowhead whale monitoring study which was funded by ESRF.

Data Analysis

Digital AVHRR imagery from bands 1 (.55-.90um) or 2 (.725-1.10um in the visible) and band 4 (10.3-11.3um in the thermal infrared) were processed using the facilities of the Institute of Ocean Sciences image processing laboratory in Sidney, B.C. Each image was first examined on the video display screen before a subset of cloud-free data over the study area was selected for further processing. Geometric distortions in the imagery, caused by the earth's curvature, satellite motion and the sensor scanning mechanism, were corrected using processing procedures which require the operator to match recognizable topographic features in the image to their location on a digital atlas map stored on the computer. Beginning with approximate orbital parameters (satellite altitude,distance along the orbit, scan angle etc.) and known latitude and longitude of several points within the image, the program calculates the exact orbital parameters (and therefore the geometry for every point in the image) by successive iteration. The corrected image data was then replotted to fit an equi-rectangular projection (a simple map in which the lines of latitude and meridians of longitude are both parallel and equi-distant) with a geometric accuracy better than 2km everywhere in the image.

Cloud and ice features in the rectified thermal and visible data were then masked (set off visually by changing the digital values in those locations to a constant and therefore uniform colour, in this case 255 = white) by relying on the fact that both cloud and ice are colder and brighter than water features in the area. Although the pack ice edge can be identified through some types of thin cloud, our current procedures do not allow consistent, unambiguous and rapid separation using digital techniques. Consequently, cloud and ice features are not differentiated for the images presented here. If this type of information is desired, it can be obtained by multi-band operations (for instance subtracting the visible band from the thermal band removes much of the thin cloud and shows up the pack edge very well; Gower, in press.) In order to facilitate analysis of the data,the coastline, latitude/longitude have also been added to each image.

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Sea surface temeperature and turbidity patterns in open water areas were determined from analysis of the thermal and visible bands respectively. The images have been contrast stretched 1 in order to improve the contrast in both temperature and turbidity patterns.

Calibration of the imagery

An approximate calibration of the band 4 thermal imagery was possible using in situ sea surface temperature recorded at the industrial drill ships as part of their hourly weather observation program and surface temperature measurements made as part of Fisheries and Oceans oceanographic cruises. The technique used was a simple 'field calibration' essentially after Tabata and Gower (1980), who found that the AVHRR band 4 digital levels are linear with sea surface temperature with a fairly constant offset. Figure 1 illustrates the relationship between observed band 4 digital counts for the locations and times corresponding to the in situ temperatures available. Because there may be a 1-2km positioning error in the geometric correction of the imagery, we have plotted the range of digital levels within 2-3km of the position of each vessel as vertical error bars. Where it was available, recorded fluctuations 1hr before and after the time of the satellite pass are shown as horizontal error bars. Since there are very few points for any one image and they are over a relatively narrow temperature range, only one calibration line has been drawn 'by eye' using the slope of the August 22 and September 11 images which showed the best fit. The exception is for the July 20 image when the two available data points fell well off the line for the relationship of the same slope but with a different Y intercept so that the line would pass through the 0.5 degree temperature near the pack-ice. The second data point for this day was in a region of considerable temperature variability.

The small number of in situ observations points for each image and the narrow temperature range sampled, plus the temporal and spatial variability obvious in the time course plots of in situ temperature does not allow a calibration more accurate than about +/-1 degree C. The data have been delivered in the form of colour 35mm slides each with a temperature scale along the bottom. The image data have been calibrated and quantized in one degree steps in order that temperature contours can be recognized. All of the data exists on disk archive at IOS in the form presented here, as well as in several earlier versions. Other presentations or colour renditions (black and white or with ship tracks) can therefore easily be prepared in the future.

Quantitative calibration of the visible imagery in terms of mg suspended material /m^3 was not possible because in situ data was not available. Our own experience has shown that band 1 is more sensitive than band 2 to upwelling radiance signals caused by variations in suspended material, however the AES data did not include this band. Consequently band 2 imagery was analysed for July. It should also be recognized that any calibration obtained for visible band imagery will show strong seasonal variation with changing sun angle.

Mapping gradients and fronts in the imagery

As part of the bowhead monitoring study we calculated a thermal gradient index which may be of interest here. The gradient for every square kilometer in the image was calculated as the maximum digital difference between the pixel representing the position of the whale and the eight pixels surrounding it (ie. a 3km x 3km square). This calculation was also performed on every pixel in both the August 22 and September 11 image in order to map the strength and position of thermal gradients. The results of this exercise are shown in figures 2 and 3.

Limitations of Satellite Imagery

While there are considerable advantages to the use of satellite data in remote areas such as the Beaufort, there are also some significant limitations which should be recognized:

1. Only the uppermost surface layer is measured. This layer is only some 50um in the case of the thermal infrared, whereas for the visible band it is an optically weighted depth depending on the amount of light absorbing and scattering particles in the water column. For the range of suspended materials in the Beaufort this is between about 5-6m and a few cm.
2. In situ data is required for calibration of remotely sensed data because there are a number of phenomena which can alter the relationship between the signal seen at spacecraft altitude and the in situ variable.
3. Both measures require a clear view of the sea from the spacecraft. Thermal and visible imagery of the sea can not be obtained through clouds. This is a severe limitation in many areas.

In spite of these limitations, useful imagery can be obtained for the Beaufort and other parts of the Arctic. When sufficient in situ data is available for cloud free parts of an image, simple linear relationships can be obtained between the uncalibrated thermal and band 1 visible NOAA-AVHRR data and sea surface temperature (+/-0.5 degree C, Tabata and Gower, 1980; Borstad 1985) and the weight of surface suspended material respectively (+/-2mg/L, Borstad 1985). These relationships hold over a few hundred kilometers within any particular image, but because the spacecraft sensor is seeing the sum of the signal from the sea and that from the atmosphere, they will change with varying illumination (during the season) and atmospheric absorption and scattering (with spatial scales equal to meteorological events). Other factors such the nature of the suspended material itself, sea state, surface reflection and bottom reflection can also interfere (McCluney, 1975; Amos and Alfoldi, 1979). In general, the effect of the atmosphere is an additive signal in both the thermal and visible regions, and an experienced analyst can recognize areas in which atmospheric interference will be a problem by the presence of cloud, the spatial patterns of visible radiance and increases in visible band radiance.

Surface Oceanographic Features in the Southeastern Beaufort Sea, Summer 1984

What follows is a qualitative analysis of the four NOAA 7 AVHRR images obtained as part of this project, supplemented by five images obtained from the University of British Columbia as part of the 1984-ESRF sponsored bowhead whale survey (Harwood and Borstad, 1985). Weather and ice information are largely from AES pilot briefings and ice condition reports obtained by the whale survey crew during the field operations and are supplemented by their visual observations.

July

An earlier than normal break-up pattern was experienced in all areas of the southeastern Beaufort Sea during early July. In part due to generally offshore (easterly) winds during the first three weeks of July, this was a period of expansion in the area of open water and retreat of the ice edge. The first images obtained from AES show a three day sequence (9th, 10th and 11th) during these easterly winds and provide graphic evidence of the large and rapid water movements which can occur in the Beaufort. Warm water distributed along the Tuktoyaktuk Peninsula on the 9th was moved northward and cold water appeared along the shore. Some northward movement of the pack-ice is also detectable and very cold water can be seen just south of the ice edge, presumably cold subsurface water coming to the surface in the lee of moving ice.

By mid-July, the main pack-ice edge was located just north of the drilling sites approximately 80 km offshore. Giant ice floes (over 10 km across) were drifting westward out of Amundsen Gulf. Frequent periods of westerly, onshore winds throughout the last part of July and the first two weeks of August reversed this trend however. During this general contraction of the open water area, almost all thermal structure outside of the turbidity plume was erased and the plume itself was pushed back against the coast, roughly following the 10m isobath. The July 20 image was acquired during the early part of this contraction. Its distribution along the Tuktoyaktuk peninsula and the very sharp plume edge are typical of imagery acquired during the westerly or northwesterly winds. Later images had even less open water showing and were not processed.

August

During August there were frequent periods of westerly wind, particularly during the latter half of the month and average air temperature were below normal. As a result of this wind regime, there was a general onshore drift at the sea surface and the width of the open water area along the Tuktoyaktuk peninsula was reduced to 30-70 km. Open (4/10 to 6/10 concentration) areas of first year and multi-year ice drifted throughout the hydrocarbon exploration zone.

Only one cloud-free satellite image (August 22) was obtained for late August (although, more is probably available for the period August 1 - 15). The distribution of temperature and turbidity patterns on August 22 suggests a transition from an 'eastwards plume' to a 'westwards plume' consistent with the change in wind regime four days before this image. It would be interesting to examine current meter records or a time series of drill ship temperature / salinity data over this period in an attempt to gain some understanding of the subsurface dynamics during this change in regime.

A large body of very bright (turbid) water can be seen around Richard's Island, but relatively little is evident along the Tuktoyaktuk Peninsula. On the outer shelf, a series of sharp thermal fronts (many greater than 1 degree C / km) separated warmer water close to the coast from colder water in the vicinity of the ice pack. Thermal and turbidity contrast in the small cloud and ice free area surrounding Cape Bathurst was much less, because of the distance from the source of warm, turbid water (the Mackenzie River) and the proximity of the ice pack. In spite of this, there are manifestations of vigourous surface water movements which appear to be associated with an easterly flow past the Baillie Islands and into Amundsen Gulf. Strings or streamers of brash ice, which are created when surface currents sweep bits of ice out of loose pack ice, neatly outline several eddies and curls which we interpret as the result of a flow into an area with no free exit.

September

During the first two weeks of September, the wind regime was generally easterly. Average air temperatures over the southeastern Beaufort Sea were near normal for the first half of the month, but several degrees above normal during the second half. This in conjunction with the mean offshore drift at the sea surface resulted in mainly open water conditions in the drill site area throughout September. The leading pack-ice edge off the Tuktoyaktuk peninsula receeded to north of 71 30'N latitude (approximately 250 km offshore) by the end of the month. Variable amounts of very open (1/10 to 3/10 concentration) to open 4/10 to 6/10) pack-ice occurred south of that latitude with open water throughout the drill site and in Amundsen Gulf.

Satellite imagery was available for September 8, 11, 12, 14 and 17. While the September 11 imagery does not delineate the Northern edge of the river plume in Mackenzie Bay, its position was located with the use of aerial visual observations on that day and imagery for September 12. Combining all available data, we can show a rapid northwestward extension of a large tongue of warm, turbid water between August 22 and 27 at an average rate of 10 to 12 cm/sec and the development of a clock-wise anti-cyclonic eddy on the Tuktoyaktuk shelf (figure 4). This was coincident with a period of 15 to 40 knot northerly (onshore) winds which began on the 25th of August, and is the expected result of a northerly or easterly wind regime (Herlinveaux and de Lange Boom 1975, Macneil and Garret 1975). Between Herschel Island and Shingle Point, the river plume was separated from the coast by colder, clearer water and the sharpest gradients to be seen anywhere in this image (2.5 degrees C / km , see figure 2). The location and temperature / turbidity patterns suggest that this was a prograde, upwelling front in which the isopycnals (lines of equal density) slope upwards towards the coast (Owen, 1981; Herlinveaux and de Lange Boom, 1975). This interpretation is consistant with the combination of a less dense surface water mass flowing to the west along a coastline and the steeply shelving bottom in this region.

Elsewhere in the study area, a small warm and turbid plume can be seen issuing from Kugmallit Bay and bending towards the northwest under the influence of the easterly wind. The eastern edge of this plume, which was under a light mist or fog, was probably a retrograde, estuarine front in which the isopycnals slope outwards from the coast (Owen, 1981). The thermal gradient across this front was from 0.5 to 1 degree C / km.

There is little data with which to describe the eddy seen off the Tuktoyaktuk shelf, but it is consistant with a net drift during early September of warm, fresh less dense surface waters towards the north under the influence of easterly winds. Flow against the pack-ice may have been responsible for the circular motion and the formation of an ice string visible along the eastern edge of the eddy. Cold water was also being pulled out into the open water region and a moderate thermal gradient of 3 to 4 units/km can be seen in this area. Levels of surface suspended materials (turbidity) in the eddy and across the Tuktoyaktuk Shelf were below the limits of detection for the sensor.

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Recommendations

1. An OERD project about to get under-way at IOS will ivolve acquisition and at least preliminary examination of 4 digital tapes of NOAA7 AVHRR passes each day over the Beaufort and west coast. The preliminary screening and some geometric correction on this data will be done under the terms of the OERD contract. Checks with Jim Gower have confirmed that this data will be available for use by others, Most data will probably come from AES, however this is apparently not yet arranged. Discussions with both Jim Gower and Lynn Lewis are probably advisable.

2. Since AVHRR band 1 is more sensitive to changes in water colour due to suspended sediment than is band 2, band 1 data is preferable and should be requested from the receiving station. This may require special arrangements with AES. I have asked Jim Gower to try to get band 1 data for the OERD project.

3. The industry drill ships are an excellent source of in situ data and in spite of the difficulty in obtaining this data, this should be continued if possible. Complete time series data would be more valuable than single temperatures. These vessels also make several CTD casts each day which could give invaluable sub-surface information. Where the position of the vessels is suitable, CTD casts from three or four can be analysed as a vertical section to show the slope of isopleths across large areas and to infer flow.

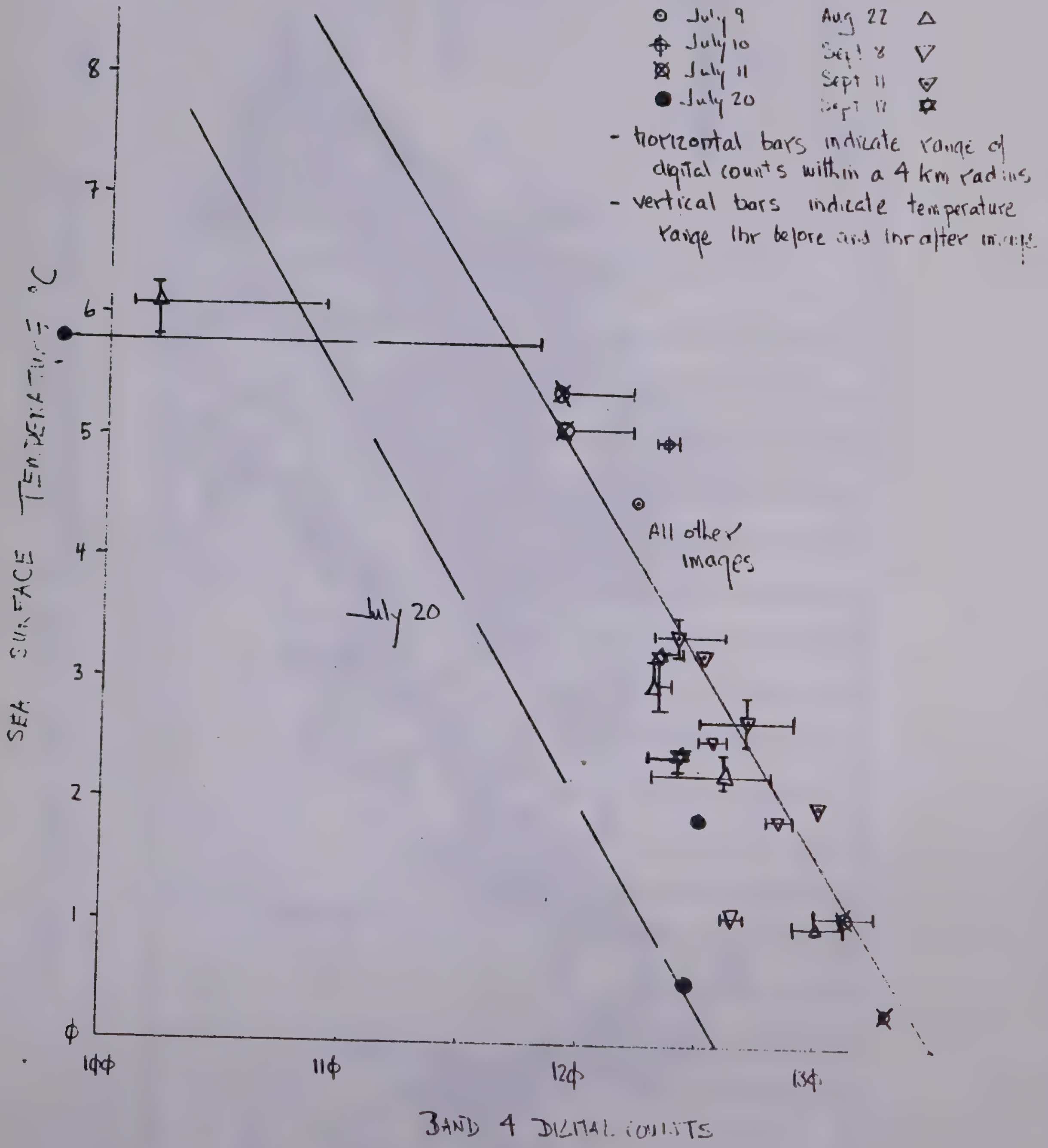
4. Most of the drill ships occupy a zone which normally has relatively low temperature contrast. Calibration of the thermal imagery could be greatly improved if in situ temperatures were available from the very warm river water or from Kugmallit Bay.

5. Fissel and Birch (1984) have shown that the winds at Tuktoyaktuk are a good indicator of the wind speed and direction offshore. It is important to be aware of this fact and that the Tuk winds are available.

6. It would be useful to implement multi-band temperature derivation algorithms at IOS. These routines use on-board calibration data which is appended to the end of each scanline of data to calculate a theoretical sea surface temperature which is reported to be within +/- .5 degree of the surface temperature. This is useful for regions where ground truth is not plentiful and should be evaluated for the Beaufort.

7. The current IOS data processing system should be supplemented with routines to facilitate production of contour maps or stippled charts. These would be easier for other scientists to use than the colour photographs which now constitute the main data product. Stippled charts can now be produced but they are very time consuming and confusing to use.

FIGURE 1. Comparison of NOAA6 + 7 AVHRR Band 4 digital counts and in situ surface temperature; S.E Beaufort Sea, Summer 1984



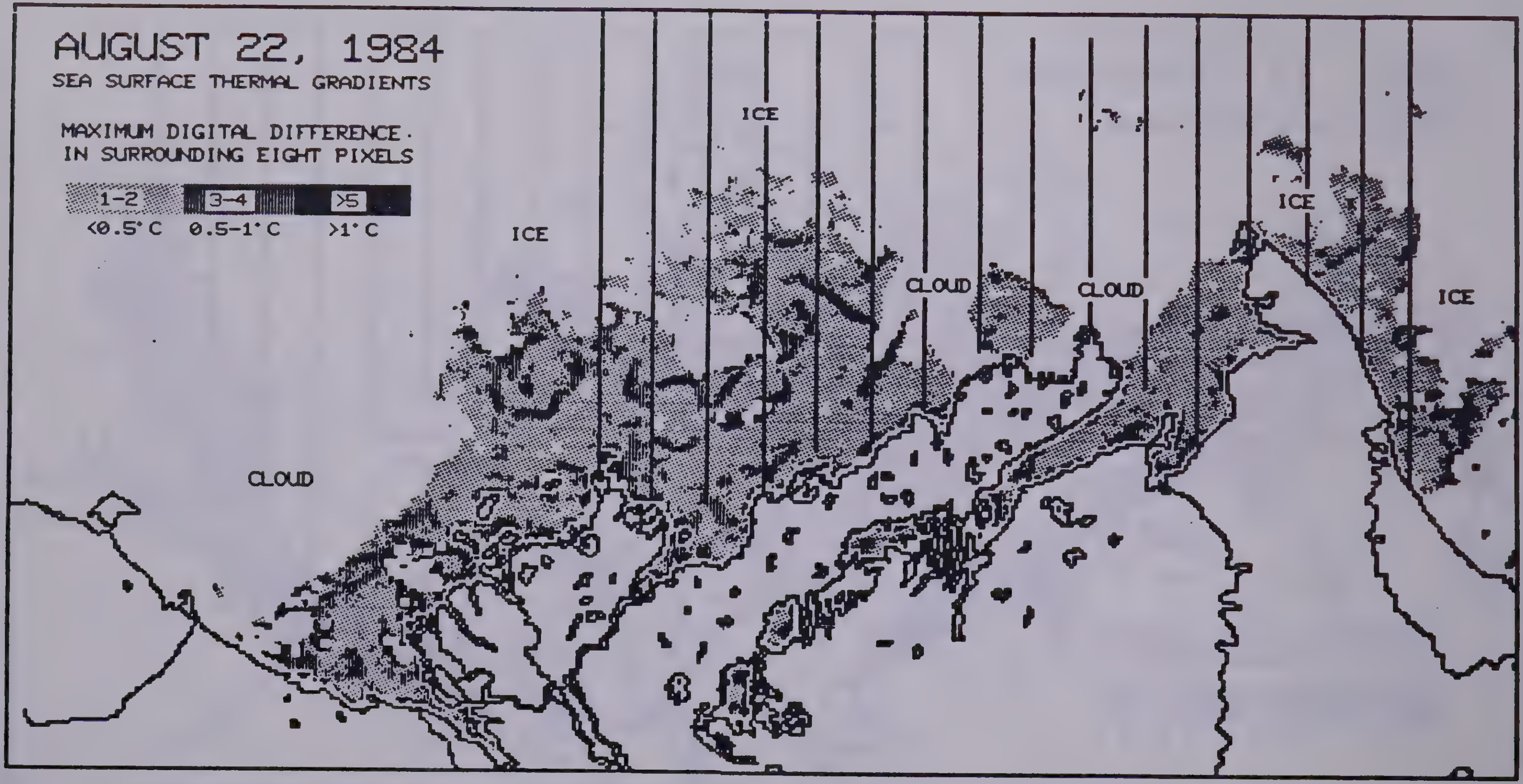

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Figure 2. Sea surface temperature gradients (degree C/2km) August 22,1984.

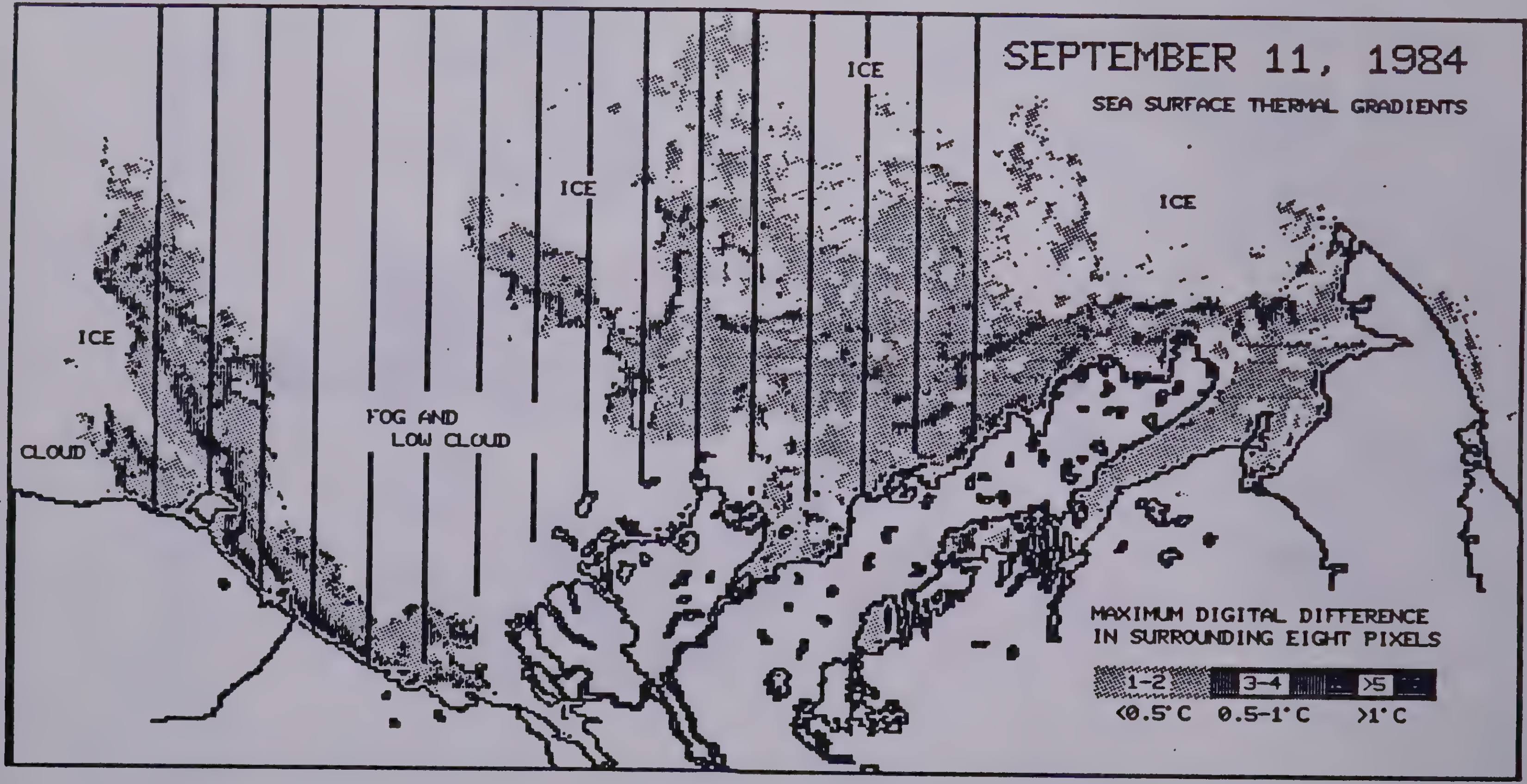
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Figure 3. Sea surface temperature gradients (degree C/2km) September 11,1984.

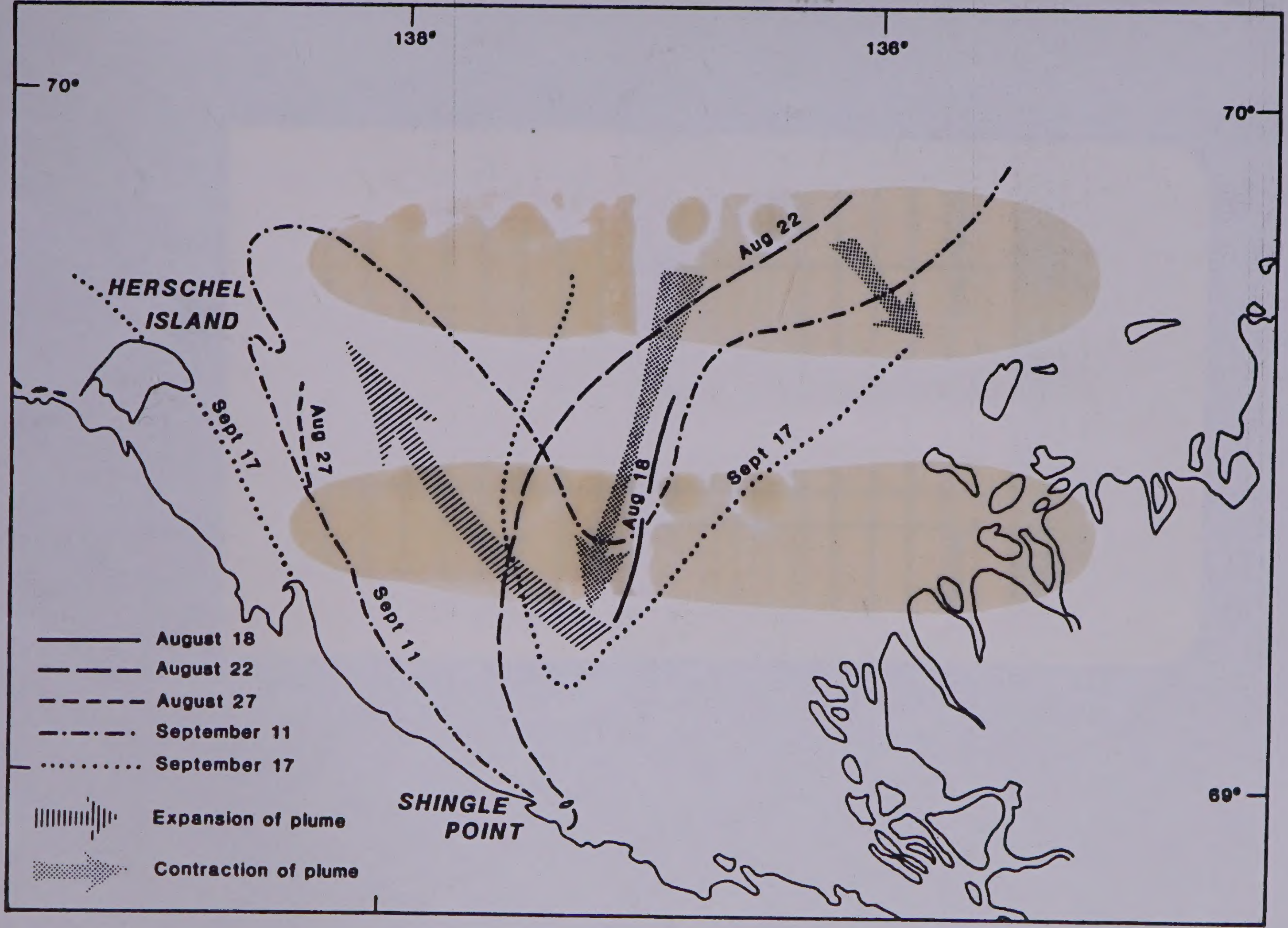

Figure 4. Evolution of the Mackenzie plume, August 18 - September 17,1984.

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